# Beyond the Standard Model Higgs Theories for Beyond the Standard Model Higgs Couplings

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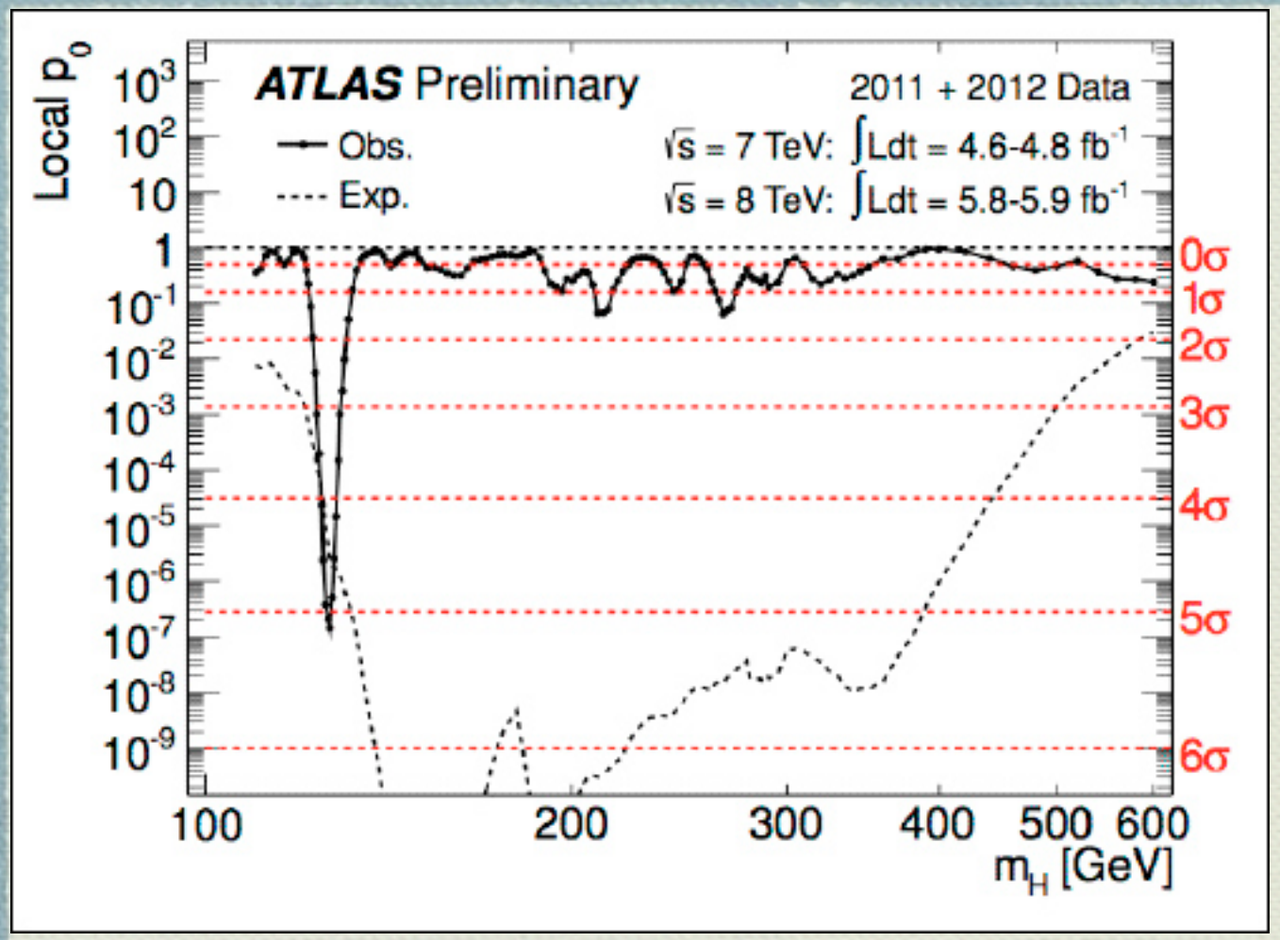
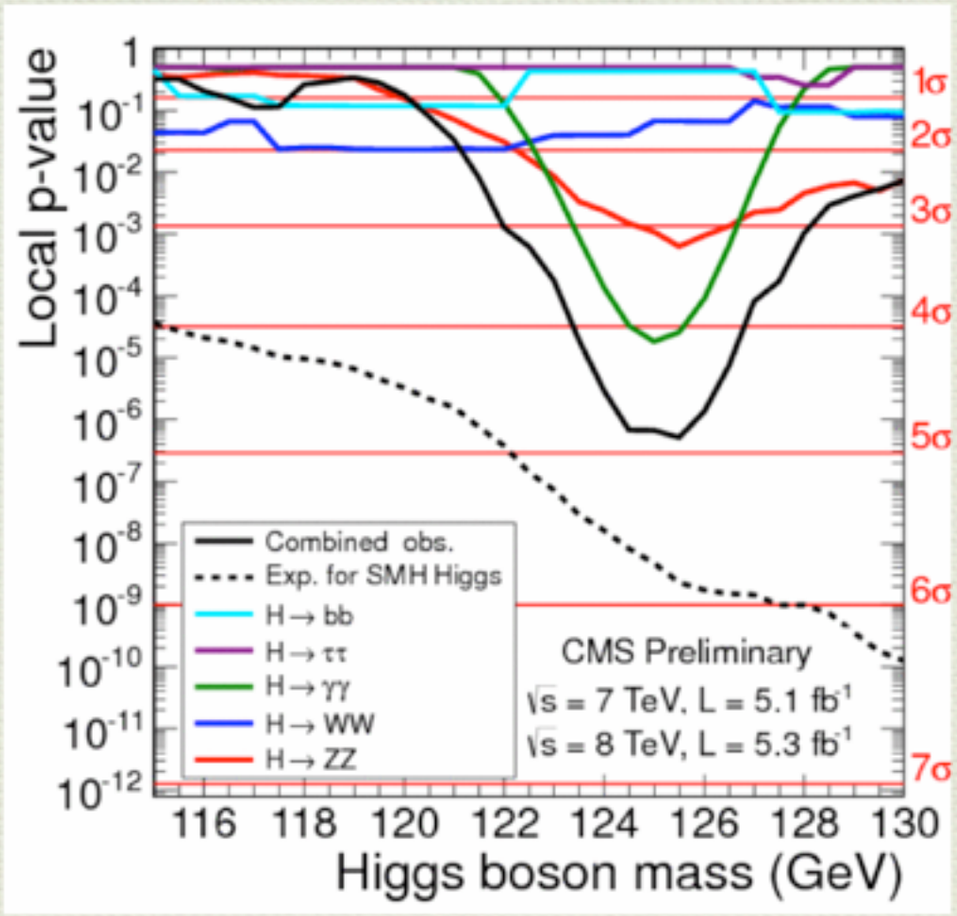
Santa Fe 2012 Workshop

# Motivation




2012 LHC analyses have confirmed excesses of 2011

# Higgsteria


Edited from: Saturday Morning Breakfast Cereal

We've discovered something that looks like the Higgs, but is it a standard Higgs?

Post-discovery, emphasis is on coupling measurements

Question: What are theory implications of coupling measurements?

# Two directions:

I) Couplings to down-type fermions suppressed?
In 1206.1058 (w/ Azatov, Craig, Galloway), we find this disfavors minimal SUSY

II) Coupling to gauge bosons enhanced?
In 1207.0493 (w/ Newby, Raj, Wanotayaroj), we explore extended Higgs sectors that allow this

# Coupling notations

Theorist conventions for gauge coupling

$$a \equiv \frac{g_{hWW}}{g^{SM}_{hWW}}$$

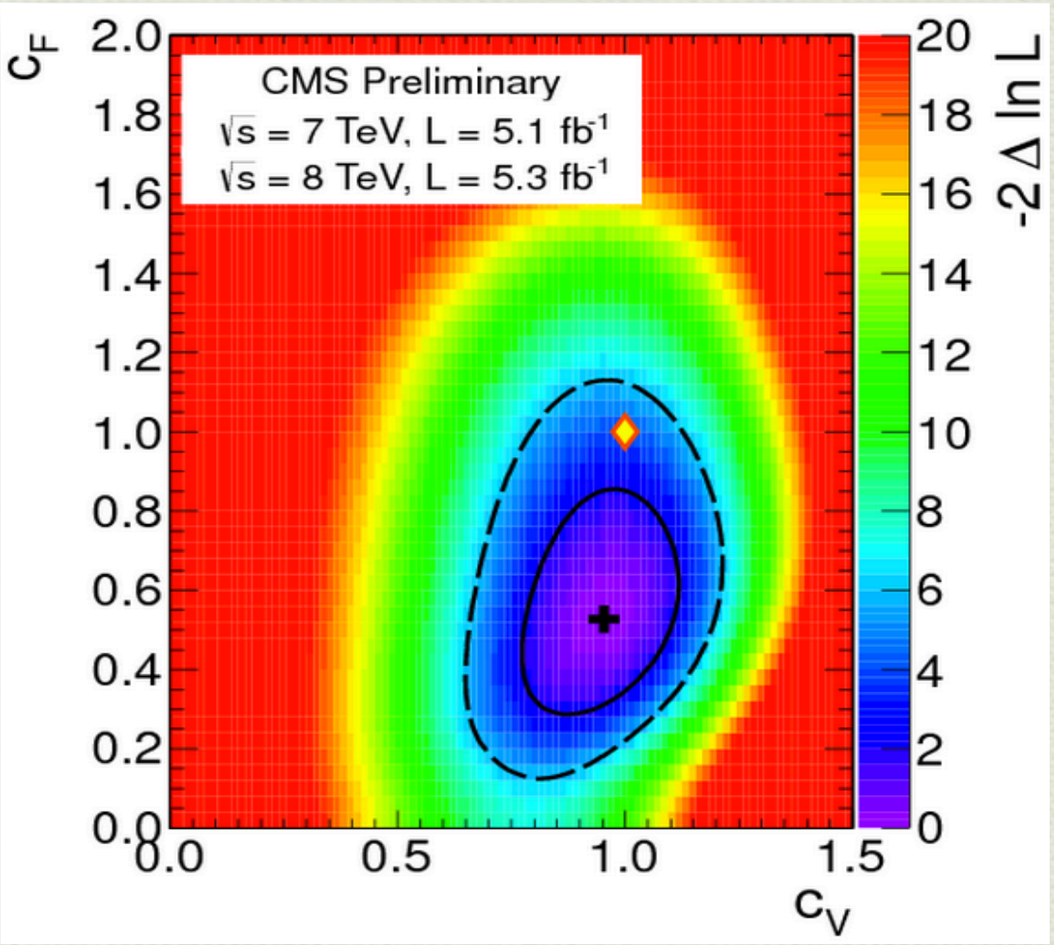
Fermion couplings

$$c_X \equiv \frac{g_{h\bar{X}X}}{g^{SM}_{h\bar{X}X}}$$

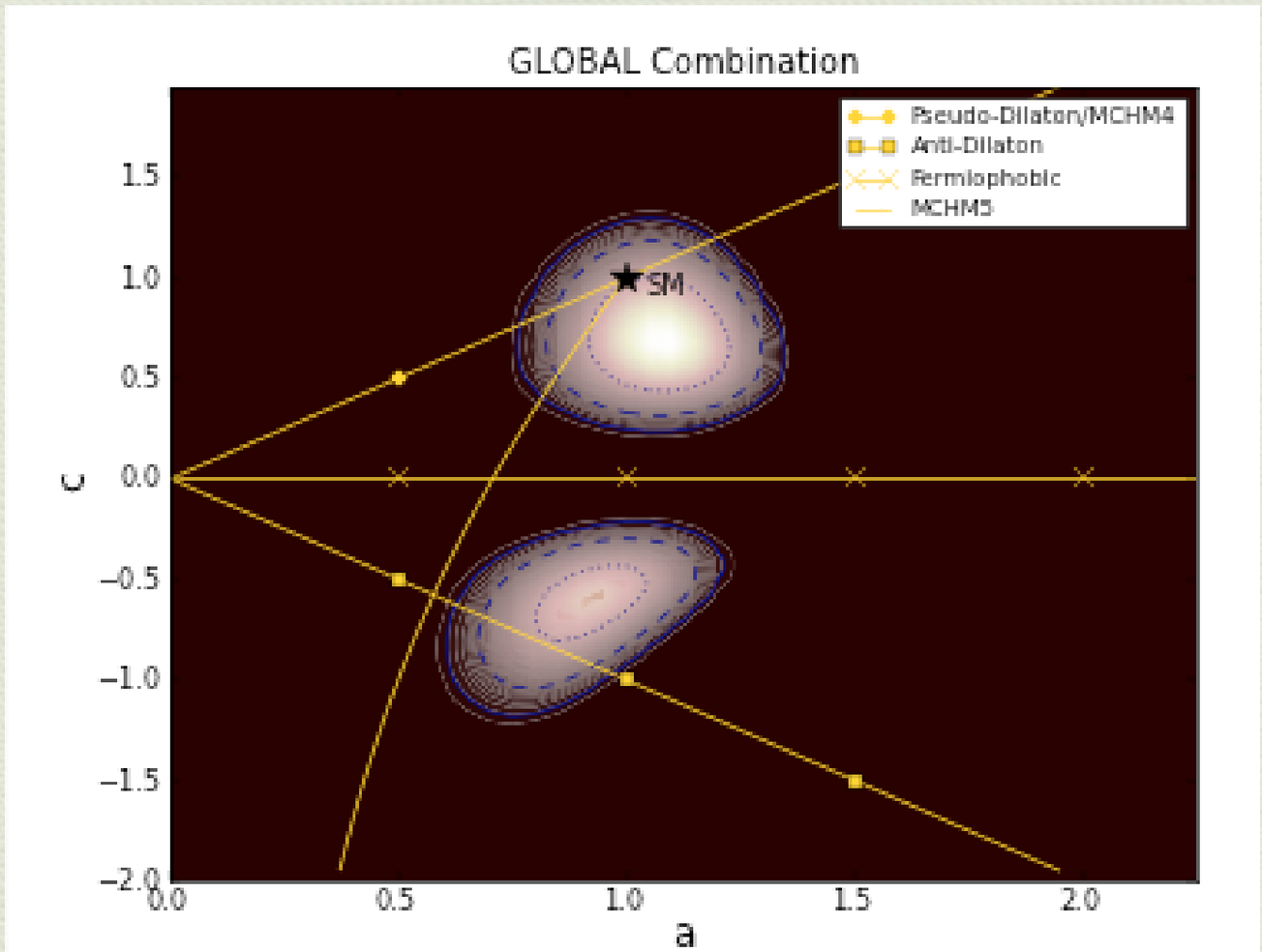
Normalized to 1 for SM value

# Fits to recent data

## Comparison of experiment and theory




CMS 2012 Fit

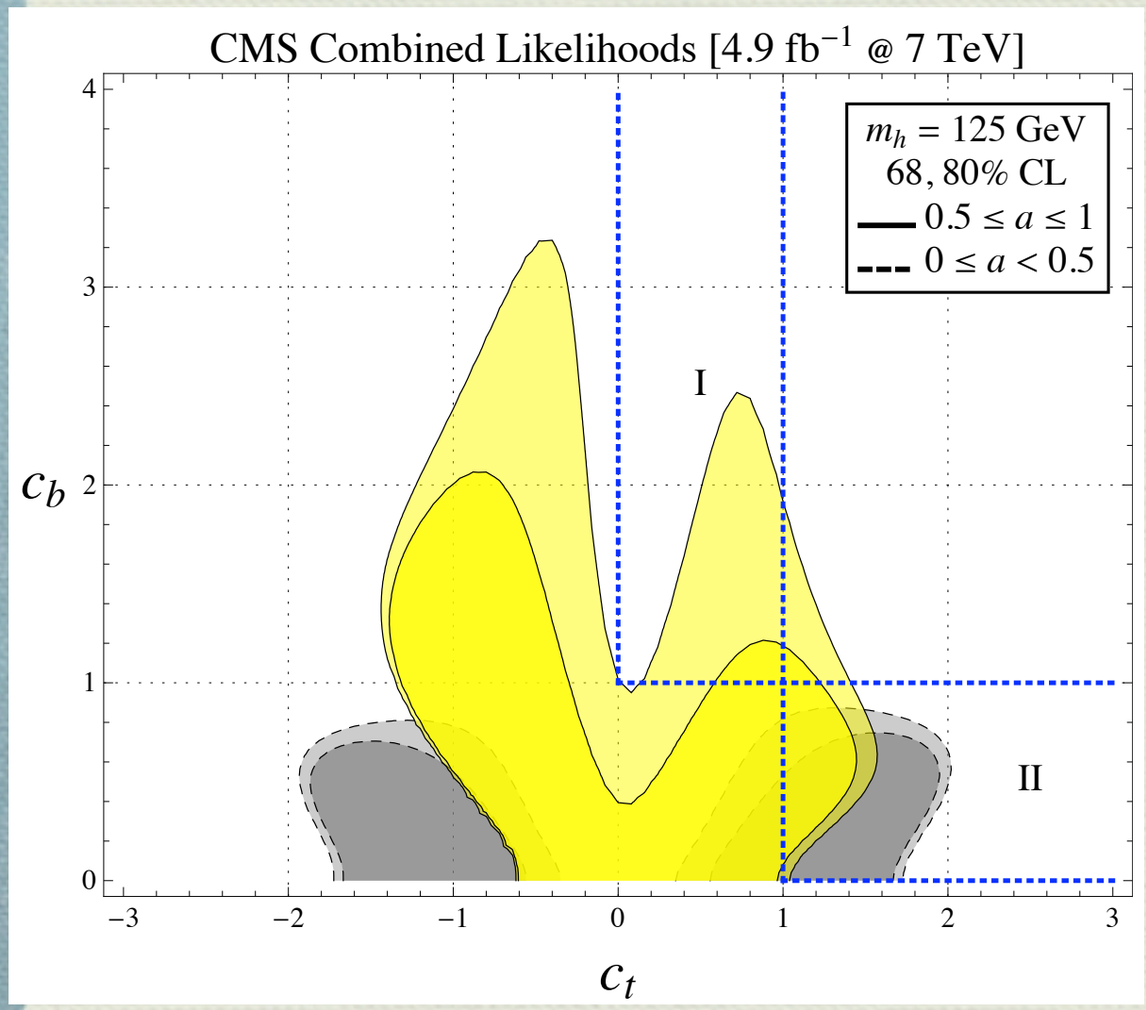



1207.1693 Ellis, You

# Suppressed down-type fermion couplings (1206.1058)

- Fermion couplings indirectly constrained now
- Top: through rate for gluon fusion (tth is starting to be analyzed)
- Bottom/tau: through effects on other branching ratios ($h \to bb$, $\tau\tau$ search becoming more important)

# Our fit to CMS 2011




VBF γγ preferred large a

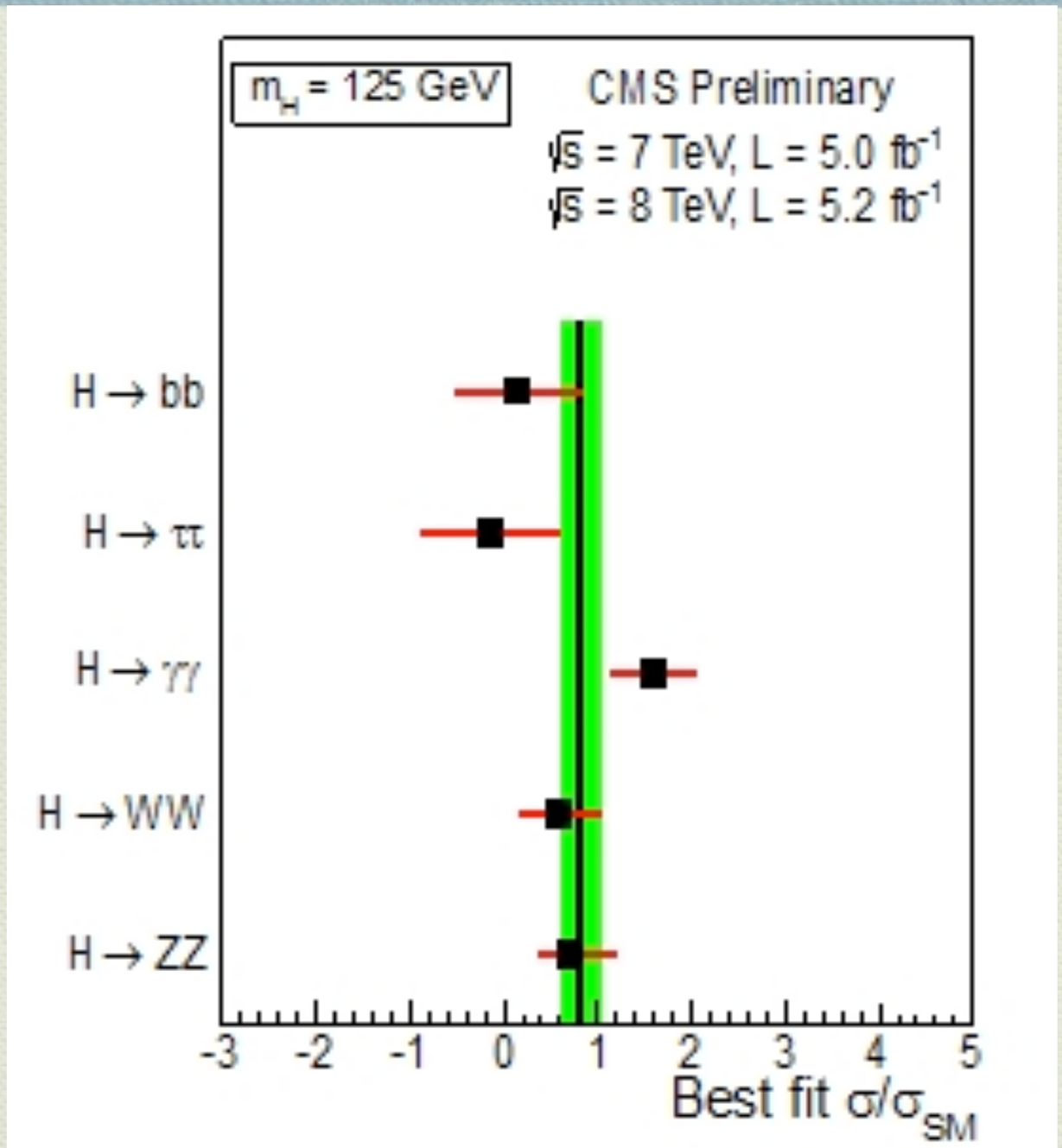
WW, ZZ channels preferred smaller a, $c_b$ and larger $c_t$

Sensitive to what data is used: e.g. Tevatron, LHC 2012

# Lack of down-type events

So far, down-type decays have no large excesses

Suggestive, but need more data

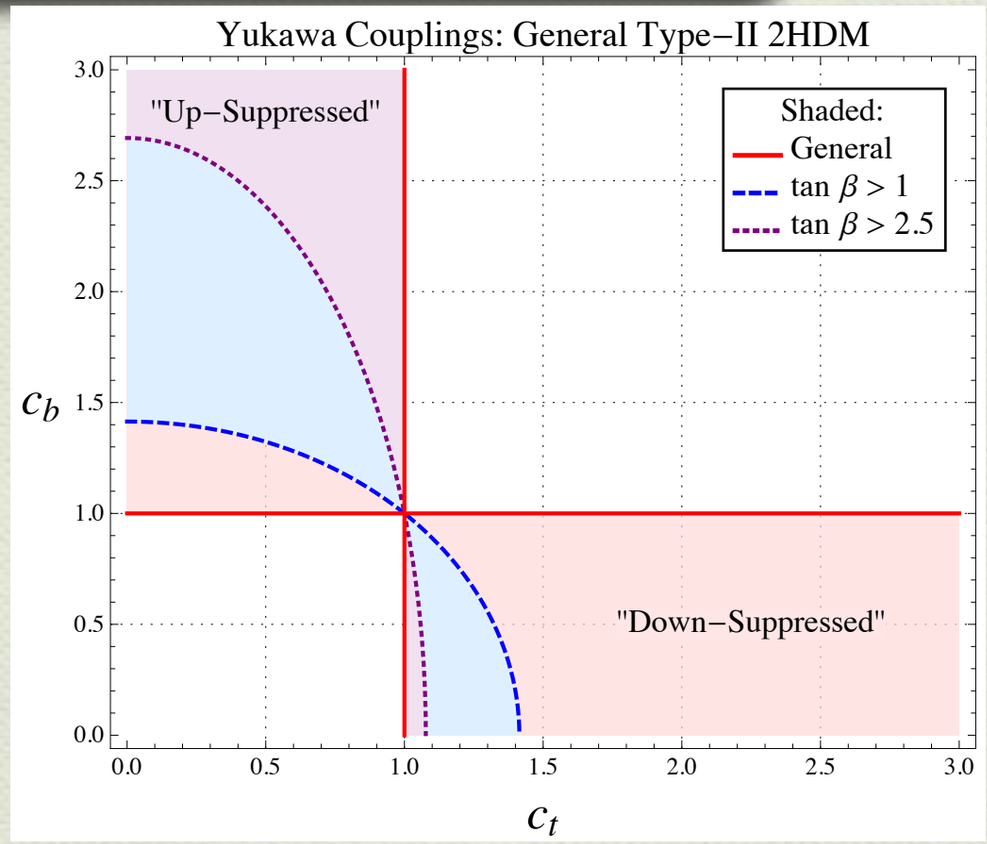


# SUSY implications
# Type II Two Higgs Doublet Model

$$a \equiv \frac{g_{hVV}}{g_{hVV}^{\rm SM}} = \sin(\beta - \alpha),$$

$$c_t \equiv \frac{g_{ht\bar{t}}}{g_{ht\bar{t}}^{\rm SM}} = \frac{\cos\alpha}{\sin\beta}, \qquad c_b \equiv \frac{g_{hb\bar{b}}}{g_{hb\bar{b}}^{\rm SM}} = -\frac{\sin\alpha}{\cos\beta},$$

General mixing angles allow suppressed down-type couplings



# Our Approach

- Analyze general two Higgs doublet model
- Determine a condition to get down-type couplings suppressed, assuming $\tan\beta > 1$
- Apply to SUSY scenarios
- Upshot: coupling measurements constrain SUSY models much like Higgs mass

# Potential

Most general quartics for neutral Higgses in 2HDM

(sorry for nonstandard notation)

$$\begin{aligned} V &= \lambda_1 \left|H_u^0\right|^4 + \lambda_2 \left|H_d^0\right|^4 - 2\lambda_3 \left|H_u^0\right|^2 \left|H_d^0\right|^2 \\ &+ \left[\lambda_4 \left|H_u^0\right|^2 H_u^0 H_d^0 + \lambda_5 \left|H_d^0\right|^2 H_u^0 H_d^0 + c.c.\right] \end{aligned}$$

Condition for down-type suppression

$$|\sin\alpha| < |\cos\beta|$$

We find a single required condition on quartics

# Condition

$$\lambda_1 \sin^2\beta - \lambda_2 \cos^2\beta - \cos(2\beta)\lambda_3 + \frac{\sin 3\beta}{2\cos\beta}\lambda_4 + \frac{\cos 3\beta}{2\sin\beta}\lambda_5 < 0$$

For MSSM, $\lambda_1 = \lambda_2 = \lambda_3 > 0$, so cannot be satisfied for $\tan\beta > 1$

Radiative corrections only help in $\alpha_{\text{eff}}$ scenario (Carena et.al.)

# For nonminimal SUSY

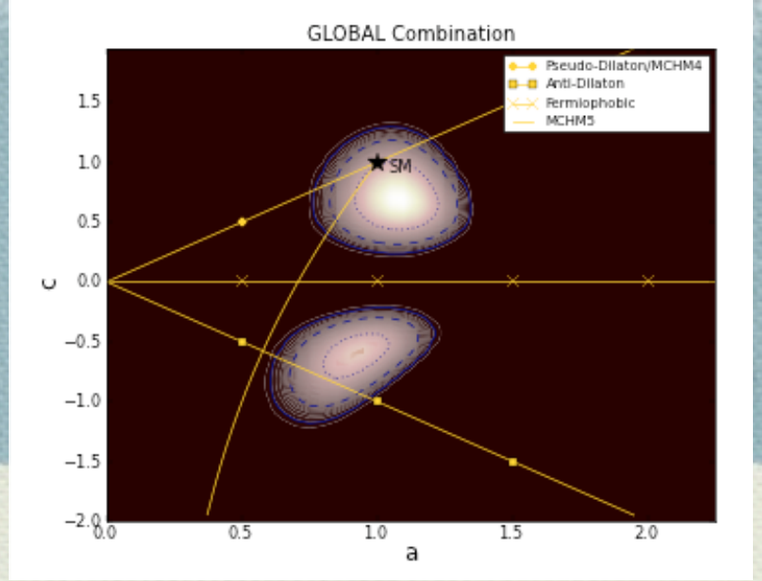
NMSSM with large λ $SH_uHd$ helps condition
(see for e.g. Hall et.al.)

Nondecoupling D-terms that maintain
D-flat direction do not work

We're currently looking into SUSY + Technicolor

Conclusion: Future analyses of bb, ττ can rule out minimal SUSY

# Enhanced couplings to WW/ZZ (1207.0493)

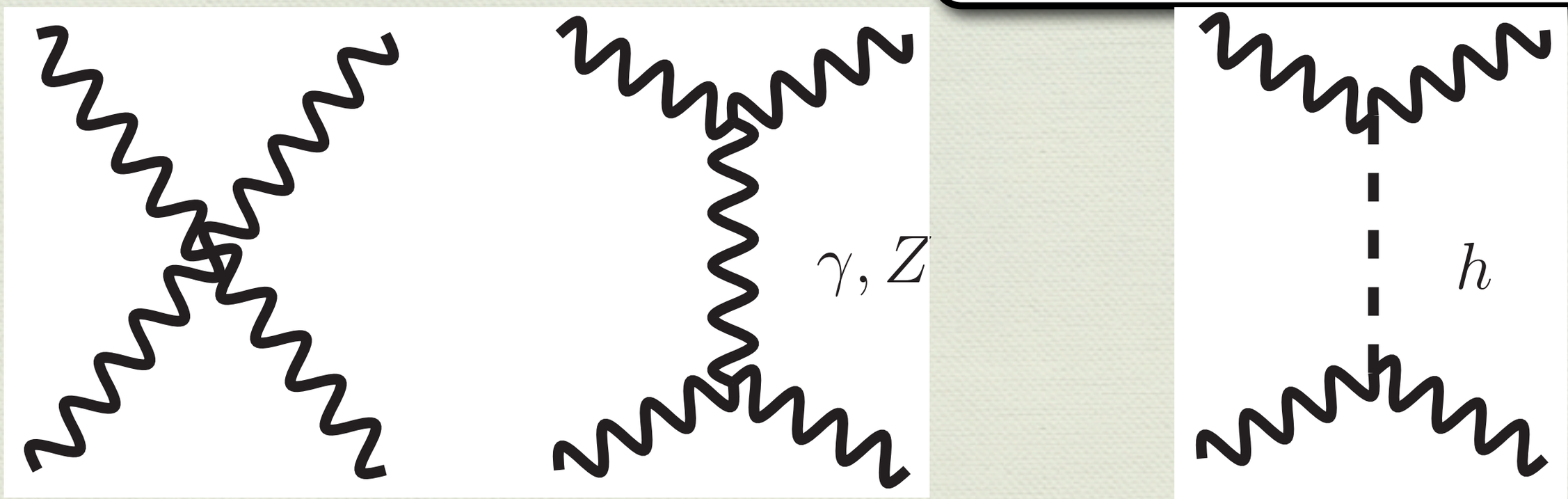



- Higgs coupling fits are model-independent, allowing all values of a, c
- Enhanced gauge couplings are constrained theoretically (requires doubly-charged Higgs)
- Looked at consistent theories (Georgi-Machacek) and their phenomenology

Requirement of doubly-charged Higgs shown by
Low, Rattazzi, Vichi and Falkowski, Rychkov, Urbano

Can be shown by unitarity

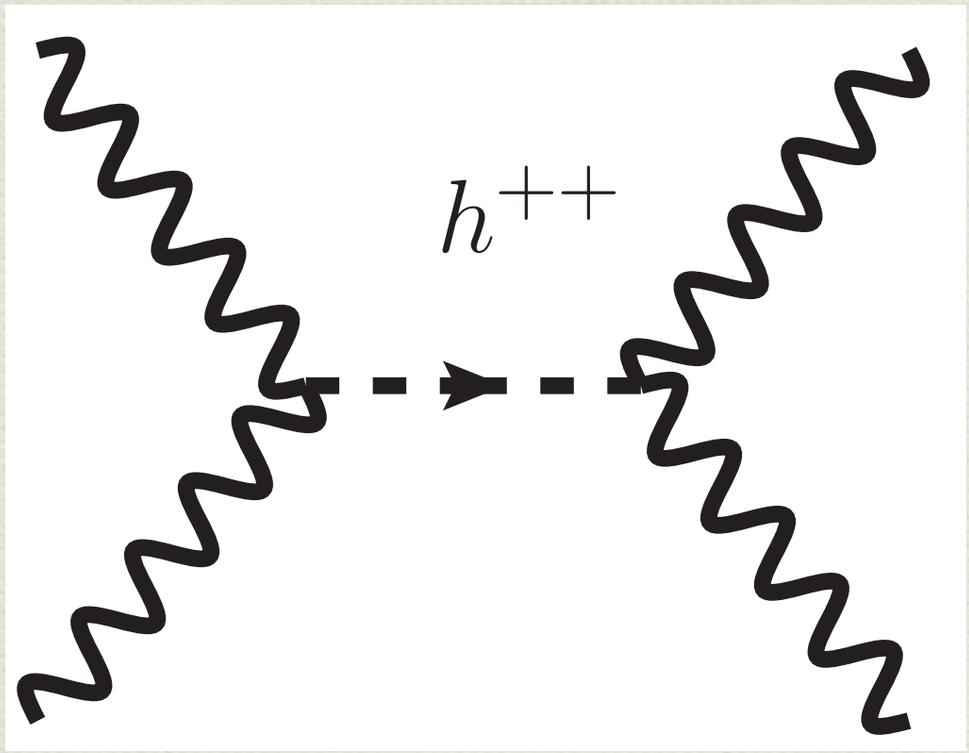
$$W_L^+ W_L^+ \to W_L^+ W_L^+$$




Unitarized if

$$\sum_i a^2_{h_i WW} = 1$$

# Doubly-charged Higgs




Doubly-charged Higgs allows enhanced a s-channel constructively interferes with SM amplitude

$$-a^2_{h--W+W+} + \sum_i a^2_{h_i WW} = 1$$

# Georgi-Machacek Model

Model with large breaking allowed by triplets

$$\phi = \begin{pmatrix} \phi^{0*} & \phi^{+} \\ \phi^{-} & \phi^{0} \end{pmatrix}, \quad \chi = \begin{pmatrix} \chi^{0} & \xi^{+} & \chi^{++} \\ \chi^{-} & \xi^{0} & \chi^{+} \\ \chi^{--} & \xi^{-} & \chi^{0*} \end{pmatrix}$$

Transform as $(2,\bar{2}),(3,\bar{3}) : SU(2)_L \times SU(2)_R$

Diagonal vevs break to custodial SU(2), allow large triplet vev contribution

$$< \phi^0 >= \frac{v \cos\theta_H}{\sqrt{2}}$$

# Spectrum (see Gunion, Vega, Wudka)

Under custodial SU(2), Higgs states consist of

Neutral singlets

Triplets

Quintuplet

$$H_1, H_1'$$

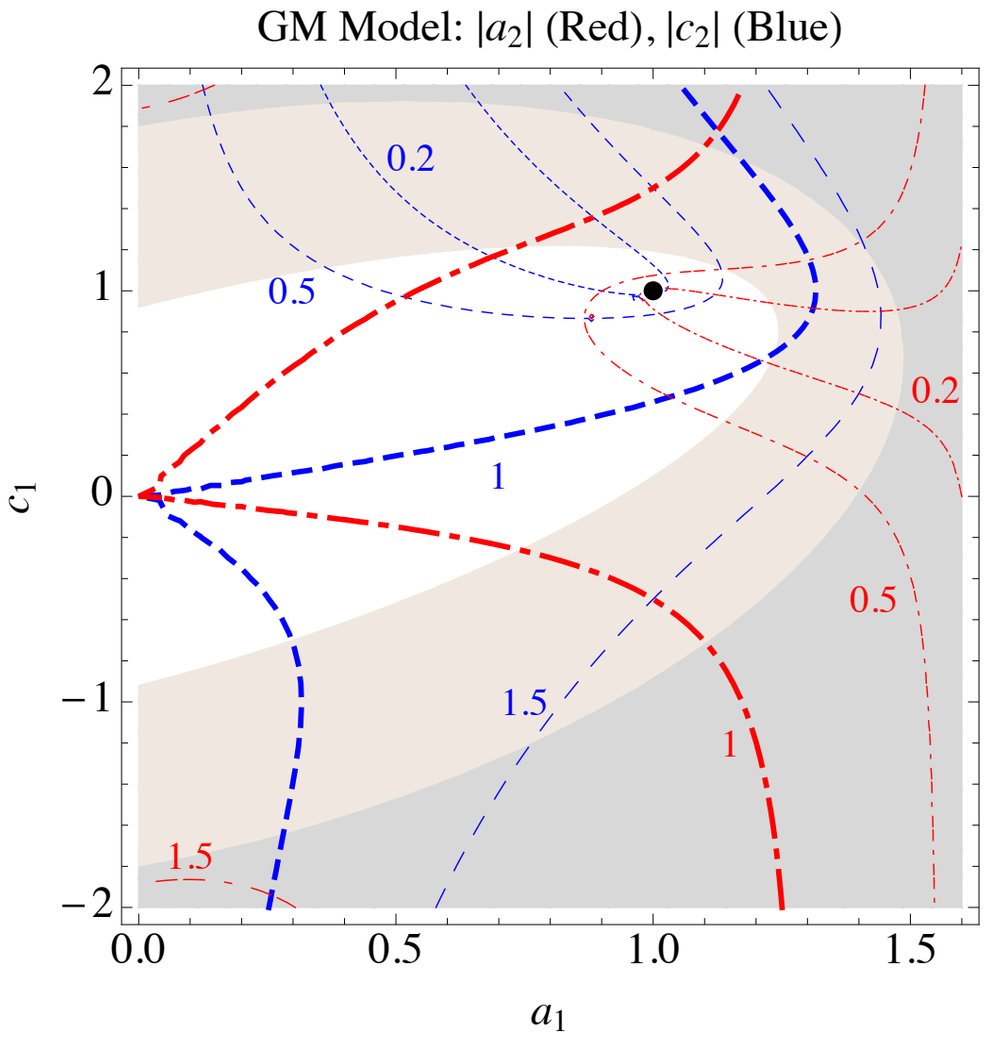
$$\left(H_3^-, H_3^0, H_3^+\right)$$

$$\left(H_5^{--}, H_5^-, H_5^0, H_5^+, H_5^{++}\right)$$

Doubly charged Higgs in $H_5$

$$a_{H_1} = \cos\theta_H, a_{H_1'} = \sqrt{8/3}\,\sin\theta_H$$

# $h_2$ couplings




Singlets mix leading to two mass eigenstates

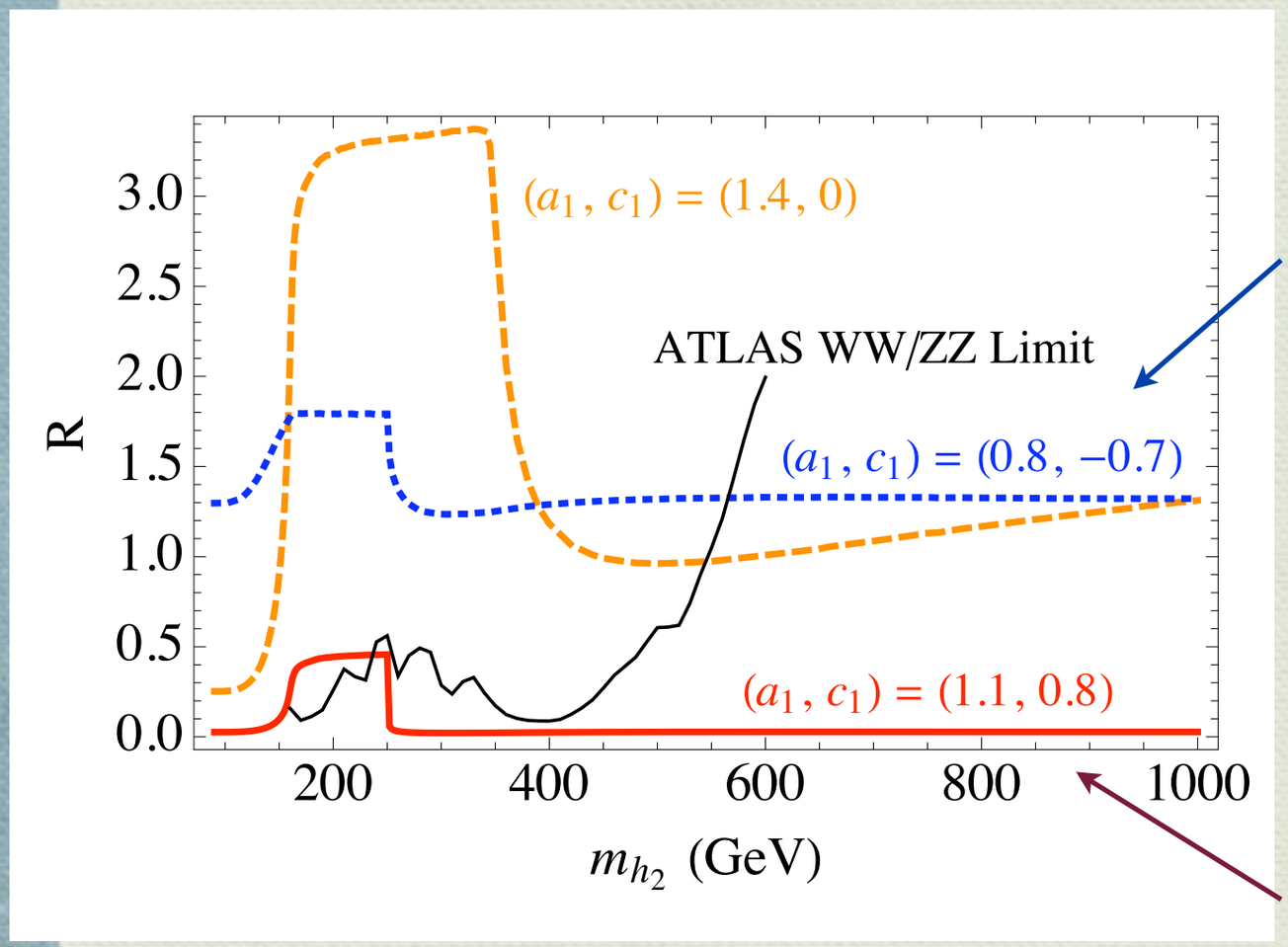
$h_1$ is taken to be Higgs that has been discovered with couplings $a_1$, $c_1$

This fixes $h_2$ couplings

Constraints on $Z \rightarrow bb$ shown in tan and gray (Haber, Logan)

# h2 Pheno

$$R = \frac{\sigma(pp \to h_2)}{\sigma(pp \to h_{SM})} \times \frac{Br(h_2 \to WW)}{Br(h_{SM} \to WW)}$$

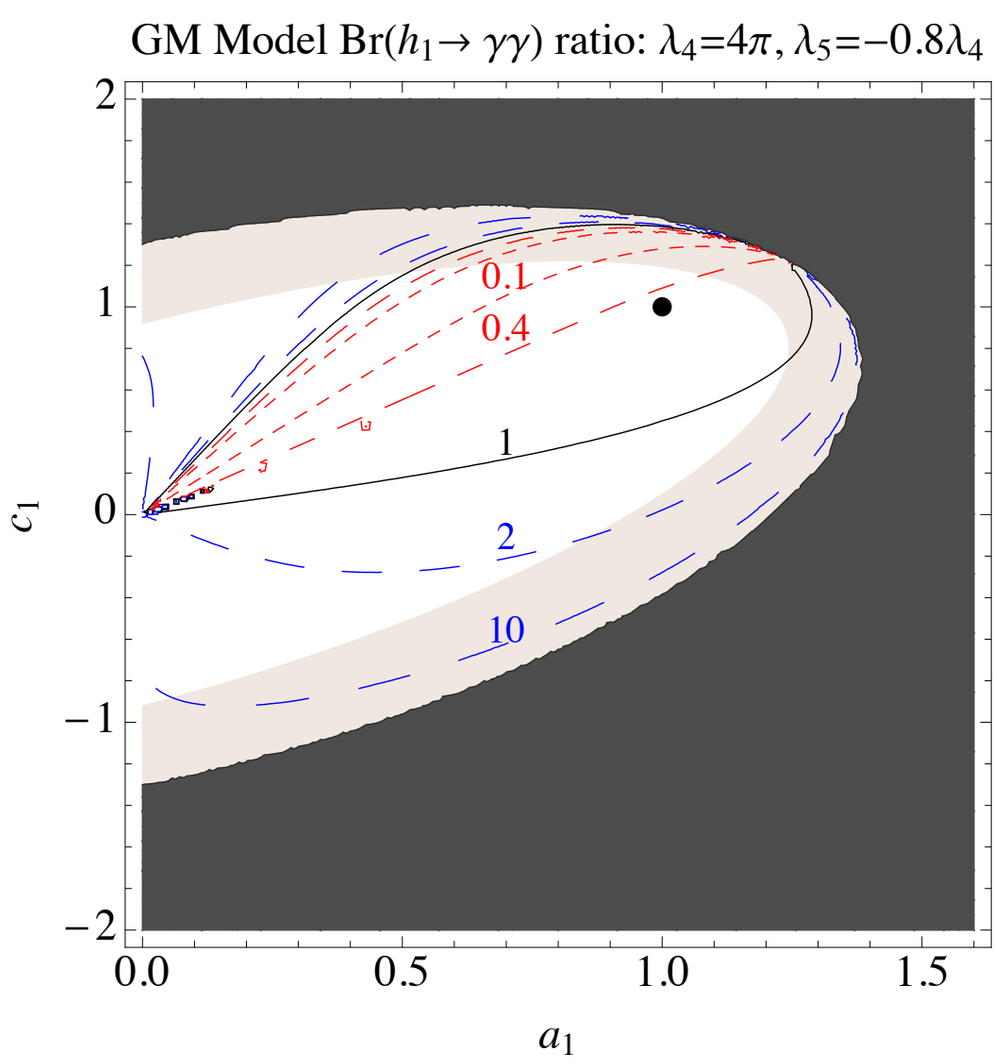



Near negative c point: couplings are strong enough to push $h_2$ above SM Higgs searches of 600 GeV

Near SM point: suppressed couplings, can be searched for in regions where SM Higgs is ruled out

In parts of parameter space, $h_2$ cascade decays to tops or $h_1$ pairs can also be important!

# $h_1 \to \gamma\gamma$




Coupling extraction complicated by charged Higgses contribution to diphoton

Typically destructive interference as shown in left plot

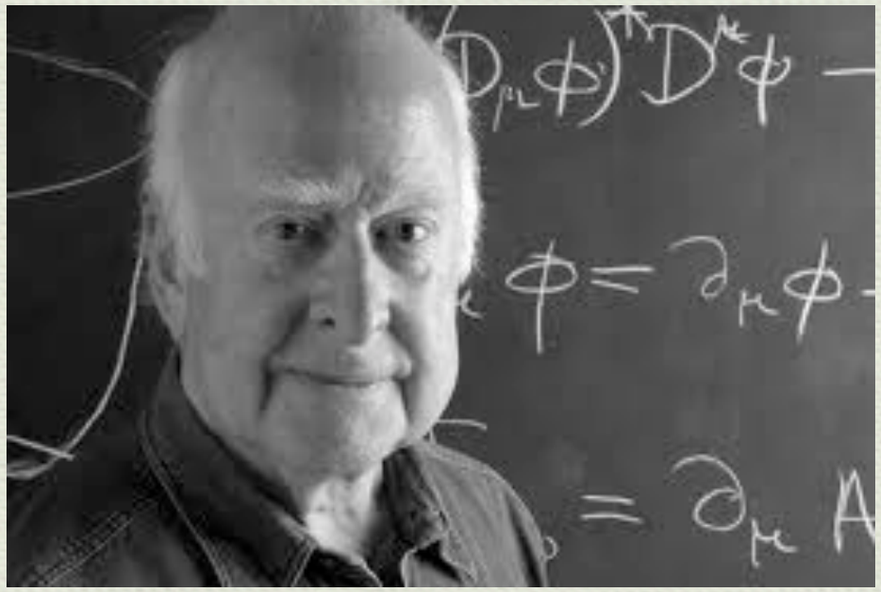
Just out last night, 1207.1718 also looked at GM model & fits

# Model dependent pheno

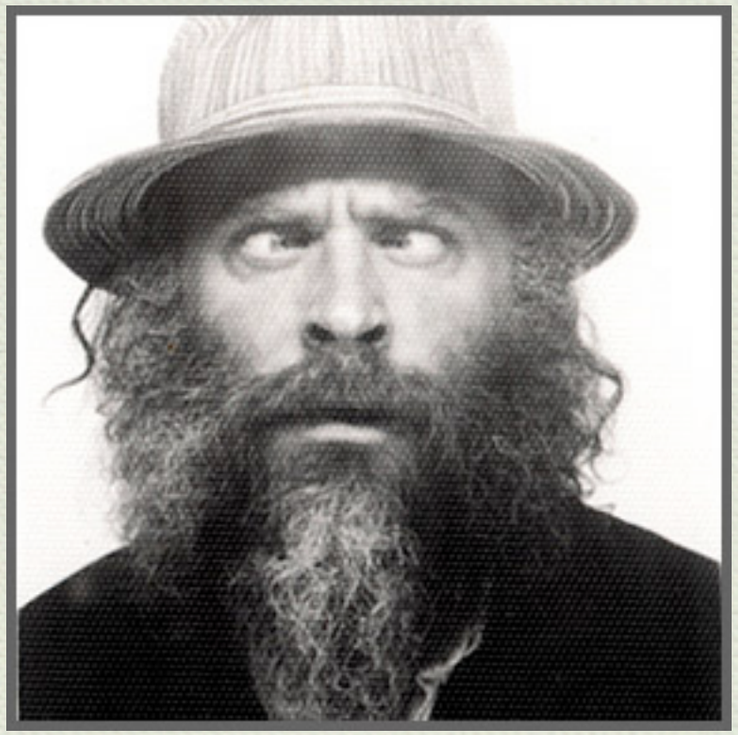
$H^{++}$ can be searched for in single production through WW fusion and its decays back to same-sign leptons (see Chiang et.al. 1202.2014)

With complicated Higgs sector, it is possible to have W/Z cascades as well as decays into pairs of lighter Higgs particles

# Looking to the Future



Peter Ware Higgs



Daniel Arcus Incus
Ululat Higgs

Is it a standard or nonstandard Higgs?
Couplings can tell us a lot!

# Conclusions

- Post-discovery, need to understand Higgs
- Early days, but worth anticipating implications of certain Higgs couplings
- Current data suggests nonstandard behavior with strong theoretical implications
- Expect ~ 15-20 $fb^{-1}$ more data, which will be very interesting!

# Thanks!